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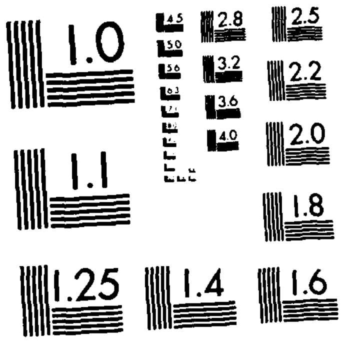

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Effects of Asymmetric Magnetospheric Currents on Cosmic Radiation

ERWIN O. FLÜCKIGER

12 July 1982

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SPACE PHYSICS DIVISION PROJECT 2311
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

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Alva T. Stair, Jr.

DR. ALVA T. STAIR, Jr
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*NRC-AFSC Research Associate on leave from Physikalisches Institut Universität Bern, Sidlerstrasse 5, CH-3012, Bern, Switzerland

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[illegible] tracing technique has been used to study the effect of [illegible] in the geomagnetic field on cosmic ray particles arriving at [illegible].

[illegible] variations of the cosmic ray cutoff [illegible] latitudes [illegible] 51.7 [illegible] corresponding to [illegible] were correlated with [illegible] in geomagnetic [illegible] for geomagnetic [illegible]

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20. (contd)

latitudes $|\Lambda| < 65°$ (that is, for McIlvain parameters $L < 5.6\ r_e$) the cutoff rigidities are most sensitive to variations of the z-component of the magnetic field within geocentric distances $r < 2\ L r_e \cos^2\Lambda$ and within a longitude sector extending from the longitude of the station up to 60° to 90° to the east of it. Within this region, magnetic perturbations being overhead and immediately to the east of the station are found to have the largest relative effect.

In the second part of the study, the effects of magnetospheric current systems, corresponding to the Boström models, on the cutoff rigidities and the asymptotic directions at Kiel, Jungfraujoch and Rome were examined. The effect of a Boström type 1 model current system (partial ring current) on cosmic ray cutoff rigidities and asymptotic directions is largest at longitudes corresponding to the western half of the region covering the main disturbances of the equatorial surface magnetic field. The dependence on longitude is more pronounced at high latitudes than at mid- and low-latitudes. At latitudes $|\Lambda| > 52°$ the magnitude of the effect depends significantly on the radius of the partial ring current. At rigidities a few GV above the main cutoff the effect on asymptotic directions is mainly restricted to a westward shift in longitude with amplitudes $|\Delta\psi| < 25°$ for a current intensity corresponding to a strong magnetic storm. At lower rigidities the magnitude of the effect increases and the asymptotic latitudes are substantially affected as well. As an interesting fact, however, the asymptotic direction corresponding to the main cutoff rigidity is found to be almost invariant, even if the main cutoff itself may have changed significantly. Boström No. 2 model currents can also considerably affect the cosmic ray cutoff rigidities as well as the asymptotic directions. The maximum effect occurs immediately outside the eastern and western border zones. The maximum amplitude of the effect decreases approximately as an exponential function of the latitudinal distance between the point of observation and the foot point of the current system in the ionosphere.

The significance of the results is discussed with respect to cosmic ray research as well as to the study of the perturbed magnetic field in the magnetosphere.

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Preface

This report summarizes a part of the research activities of the author as an NRC/AFSC Research Associate at the Air Force Geophysics Laboratory during the time period 8 December 1980 to 7 March 1982.

The author would like to express his sincere gratitude to the National Research Council for the award of a Research Associateship.

He is particularly indebted to M. A. Shea and D. F. Smart for their continuous interest in the progress of this work, for many advisory discussions, and for their generous hospitality during his stay in the United States. He also thanks the staff of the AFGL, Space Physics and Computer Divisions, for their kind assistance and support in solving many of the problems encountered during his work.

Discussions with S. I. Akasofu, D. J. Cooke, H. Debrunner, S. P. Duggal, R. A. Hoffman, M. A. Pomerantz, H. Singer and M. Sugiura were greatly appreciated and are gratefully acknowledged.

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1. INTRODUCTION

During large geomagnetic storms significant increases in the ground-level cosmic ray intensity due to a depression of the cosmic ray cutoff rigidities have been observed with amplitudes depending both on geomagnetic latitude and local time (Arens;[1] Debrunner et al;[2] and references therein). It is assumed that this effect originates from current systems developing in the earth's magnetosphere during the main phase of a geomagnetic storm. Accordingly, several attempts have been made to correlate the variations of the cosmic ray cutoff rigidities with the parameters of various current systems.[3,4,5] Up to now, most of these studies were carried out assuming azimuthally symmetric currents, neglecting the well established longitudinal asymmetry in the geomagnetic disturbance at low- and mid-latitudes during magnetic storms. The asymmetric perturbation superposed upon a symmetric field depression has been attributed by several authors to a longitudinally limited, partial ring current with field aligned closure through the auroral ionosphere (Cummings,[6] Fukushima and Kamide,[7] and references therein). It has been the objective of the research covered by this report to study the effects of such magnetospheric current systems on the propagation of cosmic ray particles through the

(Received for publication 29 June 1982)

(Due to the large number of references cited above, they will not be listed here. See References, page 35.)

domain of the earth's magnetosphere. The corresponding results were expected to demonstrate the significance of cosmic ray measurements as an additional tool for magnetospheric studies, especially in modeling the disturbed magnetic field in the magnetosphere.

In the following, first the approach to the problem is reviewed in Section 2, and examples of the basic tools needed in the procedure are illustrated in Section 3. Then, in Section 4, the results of a simple study correlating local perturbations in the geomagnetic field with cosmic ray cutoff rigidity variations are discussed. Section 5 contains a summary of a detailed quantitative analysis on the effects of a partial ring current and of field-aligned currents on both cutoff rigidities and asymptotic directions in different latitude regions. In conclusion, the significance of the results obtained in the entire study is discussed in Section 6 for both magnetospheric and cosmic ray research.

2. METHOD OF PROCEDURE

The differential equation describing the path of a particle of charge q and momentum $\vec{p}$ in the earth's magnetic field, $\vec{B}$, is given by

$$\frac{d^2\vec{x}}{ds^2} = \frac{q}{p}\left[\frac{d\vec{x}}{ds} \times \vec{B}(\vec{x})\right] \tag{1}$$

(Rossi and Olbert[8]), where $\vec{x}$ represents the position vector, s the arc length along the trajectory, and $p = |\vec{p}|$. Unfortunately, this differential equation does not have a general analytic solution even if $\vec{B}$ is expressed as a simple dipole field. It is, therefore, common practice nowadays to study the propagation of energetic charged particles in the earth's magnetosphere by numerical calculations using a mathematical model of the earth's magnetic field.

The numerical methods for the integration of Eq. (1) are well established and corresponding computer programs have been published by several authors (McCracken et al;[9] Shea et al[10]). As is done usually in cosmic ray physics, the particles are characterized in these programs by their rigidity

---

8. Rossi, B., and Olbert, S. (1970) in Introduction to the Physics of Space, McGraw-Hill, New York.

9. McCracken, K.G., Rao, U.R., and Shea, M.A. (1962) The Trajectories of Cosmic Rays in a High Degree Simulation of the Geomagnetic Field, M.I.T. Tech. Rpt. No. 77, NYO-2670.

10. Shea, M.A., Smart, D.F., and Carmichael, H. (1976) Summary of Cutoff Rigidities Calculated With the International Geomagnetic Reference Field for Various Epochs, ERP No. 561, AFGL-TR-76-0115, ADA028978.

$$P = \frac{pc}{q} \qquad (2)$$

where c is the velocity of light. The procedures then utilize the fact that Eq. (1) remains unchanged if the signs of q and ds are reversed. The trajectory of a particle with rigidity P arriving at a specific location from a specific direction is, therefore, determined backwards by tracing the path of an identical particle, but with opposite charge, leaving that particular location in the specified direction.

The computer simulation of particle trajectories in space, that is, the trajectory-tracing technique, has been used as a basis for the procedure followed in the analysis of the effects of asymmetric magnetospheric current systems on cosmic radiation. According to this procedure, which is illustrated schematically in Figure 1, a model of the quiescent geomagnetic field had to be specified first. The main field near the earth is normally represented by a sum of spherical harmonics with coefficients determined so as to produce the best fit to experimental data. In recent years great efforts have been made to develop quantitative models able to describe the magnetic field within the entire magnetosphere. For the quiet time magnetic field configuration, several models now exist which include the contributions from magnetopause, ring and tail currents in addition to the main field (Walker[11]). In the present study, allowance had to be made for the fact that in the process of calculating a cosmic ray trajectory the magnetic field has to be evaluated at many positions and that the respective amount of computer time should stay within reasonable limits. Therefore, we have not utilized the most sophisticated models in this study. For a number of initial calculations, which were essentially intended to give a more qualitative than quantitative overview of the possible effects of local magnetic perturbations on cutoff rigidities, a simple dipole representation has been used to speed up the computations. In a following, more quantitative analysis, the quiescent magnetic field was described by the International Geomagnetic Reference Field (IGRF) appropriate for Epoch 1965.0 (IAGA Commission 2[12]). It is convenient, for this problem, to express the geomagnetic field in geomagnetic coordinates as was initially done by Mead.[13] With the quiescent geomagnetic field being specified, models of the perturbed geomagnetic field have then been constructed by superposition of the disturbance field generated by the different magnetospheric model current systems upon the quiescent magnetic field. The

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11. Walker, R.J. (1979) Quantitative modeling of planetary magnetospheric magnetic fields, in *Quantitative Modeling of Magnetospheric Processes*, Geophys. Monogr. Ser. **21**:9, edited by W.P. Olson, AGU, Washington, D.C.

12. IAGA Commission 2 Working Group 4 (1969) International Geomagnetic Reference Field 1965.0, *J. Geophys. Res.* **74** 4407.

13. [illegible] (1970) International Geomagnetic Reference Field 1965.0 in dipole [illegible], *J. Geophys. Res.* [illegible]

effects of the magnetic perturbations due to the model current systems have then been evaluated by comparing the results of trajectory calculations using both quiescent and perturbed magnetic field models.

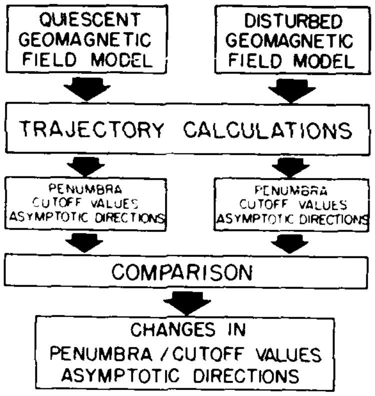

Figure 1. Schematic Representation of the Procedure Followed in the Study of the Effects of Asymmetric Magnetospheric Current Systems on Cosmic Radiation

Based on the requirements of many cosmic ray studies, two quantities were of special interest with respect to the effects of disturbances in the geomagnetic field: the cutoff rigidities of cosmic ray stations and the asymptotic directions of cosmic ray particles.

The cutoff rigidity of a specific location on the earth and of a specific direction of incidence is generally defined as the rigidity below which cosmic ray particles are inaccessible to that location from the specified direction. Following the procedure described by Shea et al[14] cosmic ray cutoff rigidities have been obtained by determining for the entire rigidity spectrum whether an individual rigidity had a trajectory accessible from infinity (that is, had an allowed trajectory) or not. For a given location with geomagnetic coordinates Λ, Φ and for a given direction, characterized by the zenith angle θ and the azimuthal angle ϕ, (see Figure 2 for the corresponding frames of reference) calculations were initiated at a rigidity well above the expected cutoff, and cosmic ray trajectories have been calculated at discrete rigidity intervals of $\Delta P = 0.01$ GV. As the calculations were progressing down through the rigidity spectrum, the results always changed from the easily allowed orbits to a complex structure of allowed, forbidden, and quasi trapped orbits and finally to trajectories which all intersected the solid earth. As illustrated

14. Shea, M.A., Smart, D.F., and McCracken, K.G. (1965) A study of vertical cutoff rigidities using sixth degree simulations of the geomagnetic field, J. Geophys. Res. 70:4117.

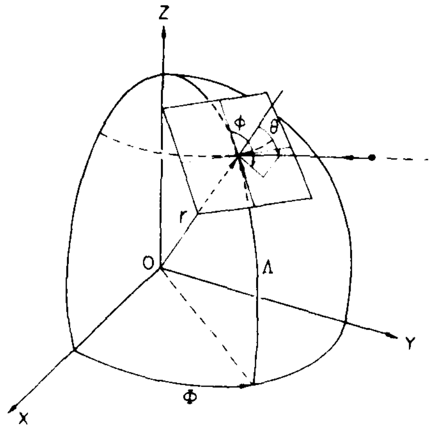

Figure 2. Frames of Reference Used in the Study of the Effects of Asymmetric Magnetospheric Currents on Cosmic Radiation

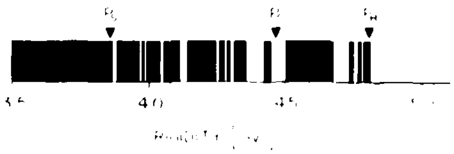

Figure 3. Penumbral Structure and Cutoff Rigidities P_M (main cutoff), P_C (effective cutoff) and P_S (Störmer cutoff), as Defined in the Text, for Cosmic Ray Particles Incident From the Vertical Direction at Jungfraujoch (geomagnetic latitude Λ_{JJ} 47.78°, geomagnetic longitude Φ_{JJ} = 90.07°). White indicates allowed rigidities and black indicates forbidden rigidities. The data refer to the International Geomagnetic Reference Field appropriate for Epoch 1965.0

in Figure 3, three distinct cutoff rigidities as defined by Shea et al[14] have been used to describe the resulting structure of allowed and forbidden trajectories:

$P_M(\Lambda, \Phi, \theta, \omega)$ the lowest rigidity above which the trajectory calculations yielded allowed orbits for all ridgities. This trajectory-derived cutoff value is called main cutoff, although its calculated value differs in many cases slightly from the actual cutoff rigidity corresponding to the main cone as defined by Lemaitre and Vallarta;[15]

15. Lemaitre, G., and Vallarta, M.S. (1936) On the allowed cone of cosmic radiation, Phys. Rev. [illegible]

$P_S(\Lambda, \Phi, \theta, \phi)$ the lowest rigidity for which the trajectory calculations yielded an allowed orbit. For the past 15 years this trajectory-derived value has been referred to as the Störmer cutoff, although its calculated value is in most cases well above the actual cutoff rigidity corresponding to the Störmer cone as defined by Störmer;[16]

$P_C(\Lambda, \Phi, \theta, \phi)$ the effective cutoff, given by

$$P_C(\Lambda, \Phi, \theta, \phi) = P_M(\Lambda, \Phi, \theta, \phi) - \int_{P_S(\Lambda, \Phi, \theta, \phi)}^{P_M(\Lambda, \Phi, \theta, \phi)} C(P; \Lambda, \Phi, \theta, \phi)\, dP$$

where

$$C(P; \Lambda, \Phi, \theta, \phi) = \begin{cases} 1 \text{ if the orbit corresponding to P is allowed} \\ 0 \text{ if the orbit corresponding to P is forbidden.} \end{cases}$$

As illustrated in Figure 4, the asymptotic direction of a cosmic ray particle having a specific rigidity and arriving at a specific location on the earth from a specific direction of incidence is the direction of motion which this particle had in interplanetary space prior to its interaction with the earth's magnetic field. It is obvious that asymptotic directions are a primary means of relating cosmic ray intensity variations at the earth with the direction of the particles in interplanetary space (McCracken et al[9, 17]). The trajectory-tracing method enables an accurate determination of asymptotic directions for a specific model of the earth's magnetic field (Shea and Smart[18]). In the relatively simple field models used in this analysis the asymptotic direction of a particle has been determined by its direction of motion, expressed in terms of the geocentric coordinate system, at 25 earth radii, where the effects of the geomagnetic field on the orbit become insignificant.

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16. Störmer, C. (1955) The Polar Aurora, Oxford University Press, Fair Lawn, New Jersey.

17. McCracken, K.G., Rao, U.R., Fowler, B.C., Shea, M.A., and Smart, D.F. (1968) Cosmic Rays, Annals of the IQSY, Vol. 1, (Geophysical Measurements: Techniques, Observational Schedules and Treatment of Data), edited by C.M. Minnis, Chapter 14, 198, The MIT Press, Cambridge, Massachusetts.

18. Shea, M.A., and Smart, D.F. (1975) Asymptotic Directions and Vertical Cutoff Rigidities for Selected Cosmic-Ray Stations as Calculated Using the International Geomagnetic Reference Field Model Appropriate for Epoch 1975.0, ERP No. 510, AFCRL-TR-75-0247, AD A015736.

In order to understand specific aspects of the effects of asymmetric magnetospheric current systems on cutoff rigidities and asymptotic directions it was also necessary to study the detailed elements of particular, representative particle trajectories. For this purpose several computer programs were developed to give graphical representations of the particle orbits as well as of a number of characteristic parameters evaluated along the trajectories.

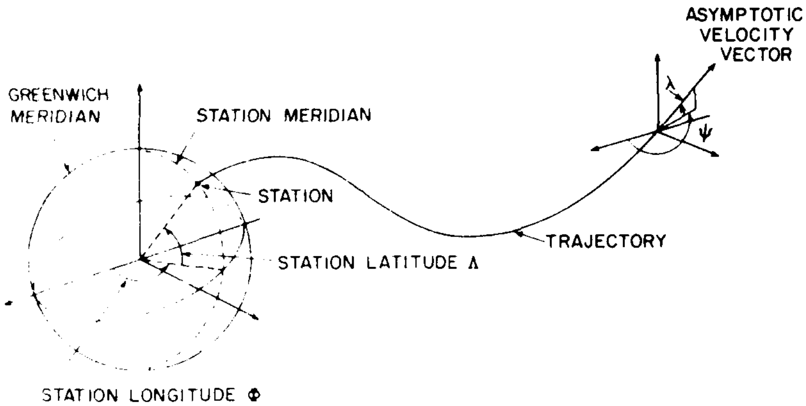

Figure 4. Illustration of the Definition of the Asymptotic Direction of Approach (according to Shea and Smart[13])

3. COMPUTER PROGRAMS FOR THE GRAPHICAL REPRESENTATION OF COSMIC RAY TRAJECTORIES

The following computer programs have been developed for the graphical representation of cosmic ray trajectories and of certain descriptive parameters:

TRJPLT1 Program to plot a side and top view of a particle trajectory in space as shown in Figure 5.

TRJPLT2 Program to plot the following parameters of a trajectory as a function of geomagnetic longitude
altitude above the surface of the earth,
[illegible] latitude,
[illegible] of Lorentz force acting on the particle (normalized to the value at the surface of the earth),
[illegible] between the velocity
[illegible]
[illegible]
[illegible] axis,
[illegible]
[illegible]

An example of a plot created by program TRJPLT2 is given in Figure 6.

TRJPLT3 Program to plot the trajectory described by a particle in the particular magnetic meridian plane which, at any time, contains the particle and rotates with the particle around the geomagnetic axis. A sample plot is given in Figure 7. This representation is useful to study the complexity of the trajectories and to classify the orbits according to their different type.

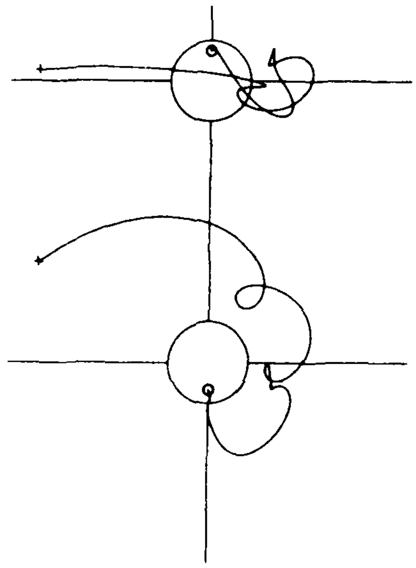

Figure 5. Side and Top View, in Geomagnetic Coordinates, of the Trajectory Within Geocentric Distances $r \leq 5r_e$ Described by a Cosmic Ray Particle With Rigidity $P = 4.42$ GV, Arriving From the Vertical Direction at Jungfraujoch (geomagnetic latitude $\lambda_{JJ} = 47.78°$, geomagnetic longitude $\Phi_{JJ} = 90.07°$, as Calculated Utilizing the International Geomagnetic Reference Field Appropriate for Epoch 1965.0

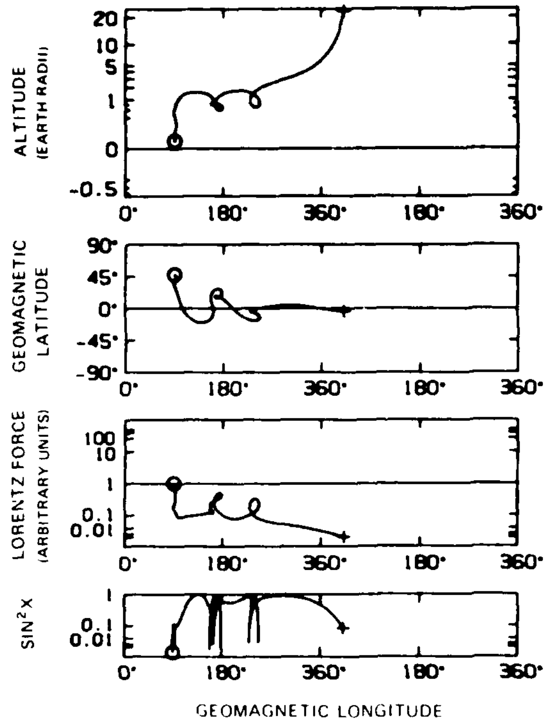

Figure 6. Graphical Representation of the Trajectory and of Additional Characteristic Parameters (as described in the text) of a Cosmic Ray Particle With Rigidity P = 4.42 GV, Arriving From the Vertical Direction at Jungfraujoch (geomagnetic latitude Λ_{JJ} = 47.78°, geomagnetic longitude Φ_{JJ} = 90.07°), as Calculated Using the International Geomagnetic Reference Field Appropriate for Epoch 1965.0

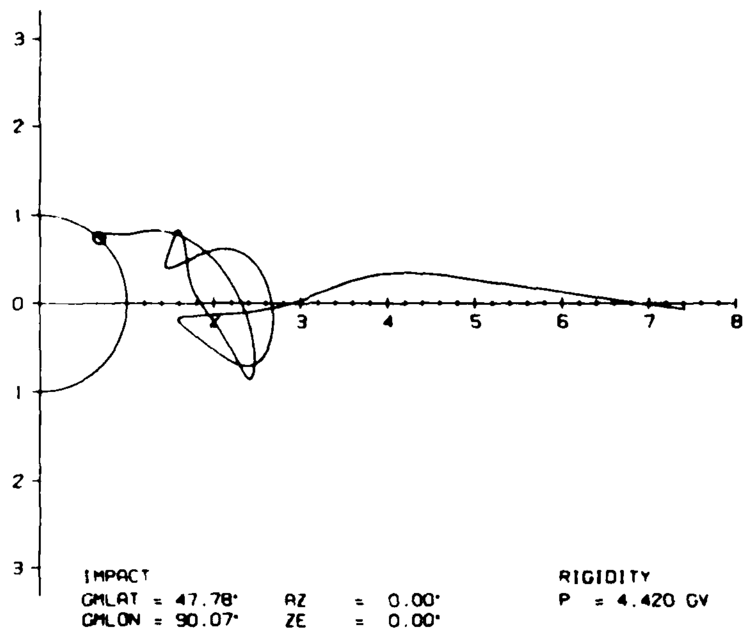

Figure 7. Trajectory Described by a Cosmic Ray Particle in the Magnetic Meridian Plane, Which, at Any Time, Contains the Particle and Rotates With the Particle Around the the Geomagnetic Axis. The parameters of the particle, the point of observation and the geomagnetic field model are the same as in Figures 5 and 6.

4. SIMPLE STUDY ON THE EFFECTS OF LOCAL DISTURBANCES OF THE GEOMAGNETIC FIELD ON COSMIC RAY CUTOFF RIGIDITIES

In order to get an insight into the general aspects of the effects of asymmetric magnetospheric current systems on cosmic radiation, an initial study was conducted correlating the variations of the cutoff rigidities of two European neutron monitor stations, Kiel and Jungfraujoch (see Table 1 for corresponding station data) with specific local perturbations of the geomagnetic field. In this analysis the quiescent geomagnetic field was represented by the field of a simple dipole with magnetic moment $M = 8.06 \cdot 10^{25}$ G-cm^3, having its origin at the center of the earth and the dipole axis intersecting the surface of the earth at 78.57°N and 69.76°W. The components of $\vec{B}$ at geocentric distance r, geomagnetic latitude Λ and geomagnetic longitude Φ were, therefore, given by

$$\left.\begin{aligned} B_r(r, \Lambda, \Phi) &= -(2M/r^3)\sin\Lambda \\ B_\Lambda(r, \Lambda, \Phi) &= (M/r^3)\cos\Lambda \\ B_\Phi(r, \Lambda, \Phi) &= 0 \end{aligned}\right\} . \tag{3}$$

In the first part of the study the perturbed geomagnetic field was modeled by superposing the disturbance field, $\vec{B}'$,

$$\vec{B}'(r, \Lambda, \Phi) = \begin{cases} \vec{B}''(r, \Lambda, \Phi) & r < r_B \\ 0 & r > r_B \end{cases} \tag{4}$$

on the dipole field. By varying the adjustable boundary, r_B, successively from $r_B = 1$ earth radius (r_e) to larger values it was possible to analyze the dependence of the cutoff changes on the radial structure of geomagnetic perturbations. In order to facilitate comparisons of the results with the theoretical work by Treiman[3] on the effect of the equatorial ring current on cosmic ray intensity, $\vec{B}''$ was chosen so as to describe the magnetic field of a current sheet flowing on a geocentric sphere with radius a and having a current density proportional to the cosine of the geomagnatic latitude. Therefore, $\vec{B}''$ was defined by

$$\left.\begin{aligned} B''_r(r, \Lambda, \Phi) &= (2M_R/a^3)\sin\Lambda \\ B''_\Lambda(r, \Lambda, \Phi) &= (2M_R/a^3)\cos\Lambda \\ B''_\Phi(r, \Lambda, \Phi) &= 0 \end{aligned}\right\} \quad \text{for } r < a \tag{5a}$$

and

$$
\left.\begin{aligned}
B''_r(r, \Lambda, \Phi) &= (2M_R/r^3) \quad \sin\Lambda \\
B''_\Lambda(r, \Lambda, \Phi) &= -(M_R/r^3) \quad \cos\Lambda \\
B''_\Phi(r, \Lambda, \Phi) &= 0
\end{aligned}\right\} \quad \text{for } r > a \tag{5b}
$$

respectively, with M_R denoting the magnetic moment of the ring current. It can easily be seen from Eqs. (5a, 5b) that inside the current sheet, that is, for $r \leq a$, the disturbance field is uniform in the z-direction with

$$
B''_z(r, \Lambda, \Phi) = 2\,M_R/a^3 \tag{6}
$$

and that for $r > a$ the disturbance field $\vec{B}''$ is a simple dipole field.

Table 1. List of Locations Used in the Analysis of the Effects of Asymmetric Magnetospheric Current Systems on Cosmic Radiation

	Kiel	Jungfraujoch	Rome
Geographic coordinates:*			
- latitude Λ	54.30°	46.50°	41.90°
- longitude E Φ	10.10°	8.00°	12.52°
Geomagnetic coordinates:*			
- latitude Λ	54.77°	47.78°	42.46°
- longitude E Φ	95.77°	89.82°	92.42°
L-Value*	2.59	1.94	1.59
Vertical cutoff rigidity in the geomagnetic dipole field			
--main cutoff P_M	1.83 GV	3.43 GV	5.09 GV
--effective cutoff P_C	1.70 GV	3.22 GV	4.74 GV
Vertical cutoff rigidity in the IGRF, Epoch 1965.0			
- main cutoff P_M	2.39 GV	4.81 GV	6.35 GV
- effective cutoff P_C	2.26 GV	4.47 GV	6.16 GV

*Buhmann et al[19]

19. Buhmann, R.W., Roederer, J.G., Shea, M.A., and Smart, D.F. (1974) Report UAG-38, Master Station List for Solar-Terrestrial Physics Data at WDC-A for Solar Terrestrial Physics, WDC-A for STP.

The results of these calculations are illustrated in Figures 8 and 9. In Figure 8 the relative changes in the vertical main cutoff and in the effective vertical cutoff rigidity at Jungfraujoch are plotted as a function of the radial extent, r_B, of a magnetic perturbation according to Eq. (4) with $B''_z(r \le a) = -100$ nT and with the values a = 3, 4 and $5r_e$ for the radius of the corresponding ring current. It can be seen that for $r_B \le a$ (if $a = 3r_e$), and $r_B \le 4r_e$ (if $a \ge 4r_e$), the dependence of the relative cutoff variation $\Delta P/P$ on r_B can well be approximated by a linear function. Since $\Delta P/P$ also depends linearly on B''_z, we find in this range of r_B

$$\frac{\partial^2\left(\frac{\Delta P_{M,C}}{P_{M,C}}\right)}{\partial r_B \, \partial B''_z} \approx -3.5\% \, (r_e \cdot 100 \text{ nT})^{-1} . \qquad (7)$$

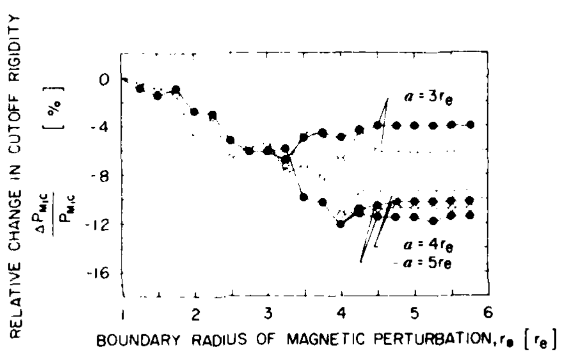

Figure 8. Relative Changes in the Vertical Main Cutoff (◇), and in the Effective Vertical Cutoff Rigidity (●) at Jungfraujoch as a Function of the Boundary Radius, r_B, of a Magnetic Disturbance According to Eqs. (4) and (5) With $B''_z(r \le a) = -100$ nT and a = 3, 4 and $5r_e$ Superposed Upon the Main Dipole Field (see text for details). The corresponding undisturbed cutoff rigidities are $P_M = 3.43$ GV, $P_C = 3.22$ GV

Furthermore, the relative cutoff changes are almost independent of r_B for $r_B > a$ (if $a = 3r_e$) and for $r_B > 4r_e$ (if $a \ge 4r_e$) with approximately equal amplitudes for all values $a \ge 4r_e$. This last result is in good qualitative agreement with the conclusions obtained by Treiman for the symmetric ring current. In Figure 9 corresponding results for Kiel obtained with the same disturbance field $B''_z(r \le a) = -100$ nT and with radii of the ring current equal to a = 4, 5, 6 and 7 r_e are shown. Although these results are in general similar to those found for

Jungfraujoch, significant differences can be observed. First of all, the dependence of the relative cutoff variation, $\Delta P/P$, on the boundary value r_B can no longer be approximated by a single linear function in the ranges $r_B < a$ (if $r_B = 4$, 5, and $6r_e$) and $r_B > 6r_e$ (if $a = 7r_e$). On the contrary, we find

$$\frac{\partial^2\left(\frac{\Delta P_{M,C}}{P_{M,C}}\right)}{\partial r_B\, \partial B''_z} = -1.5\,\%\,(r_e \cdot 100\ \mathrm{nT})^{-1} \tag{8}$$

in the region $1r_e < r_B < 2.5r_e$, and

$$\frac{\partial^2\left(\frac{\Delta P_{M,C}}{P_{M,C}}\right)}{\partial r_B\, \partial B''_z} = -7.75\,\%\,(r_e \cdot 100\ \mathrm{nT})^{-1} \tag{9}$$

for $2.5r_e < r_B < a$ (if $a = 4$, 5 or $6r_e$) and for $2.5r_e < 6r_e$ (if $a = 7r_e$). This indicates that the cutoff rigidity at Kiel is approximately five times more sensitive to perturbations of the z-component of the geomagnetic field at geocentric distances $2.5r_e < r < 6r_e$ than to equal magnetic disturbances within $1r_e < r < 2.5r_e$. It can then also be seen from the curves corresponding to $a = 6r_e$ and $a = 7r_e$ that the cutoff rigidity at Kiel is influenced by changes in the geomagnetic field within geocentric distances of up to $r \approx 6r_e$ in contrast to the corresponding value of $r \approx 4r_e$ found for Jungfraujoch.

In the second part of the analysis the disturbance field superposed upon the geomagnetic dipole field was chosen to be

$$\vec{B}'(r, \lambda, \Phi) = \begin{cases} \vec{B}''(r, \lambda, \Phi) & \text{for } \Phi_W < \Phi < \Phi_E \\ 0 & \text{elsewhere} \end{cases} \tag{10}$$

where $\vec{B}''$ was again defined by Eq. (5) and where Φ_W and Φ_E describe the geomagnetic longitude of the western and eastern boundary, respectively, of the longitude sector containing the magnetic perturbation. By varying the parameters Φ_W and Φ_E with respect to a specific location on the earth it was possible to study the dependence of the cutoff changes on the longitudinal structure of geomagnetic perturbations. Typical results of these calculations are presented in Figures 10 through 13. Figure 10 shows the relative changes in the vertical main cutoff and in the effective vertical cutoff rigidity at Jungfraujoch as a function of the longitudinal position of the center meridian, $\Phi = (\Phi_W + \Phi_E)/2$, of a magnetic perturbation with constant width $\Phi_E - \Phi_W = 90°$, flux density $B''_z(r < a) = -100$ nT and $a = 4r_e$. It is evident that both

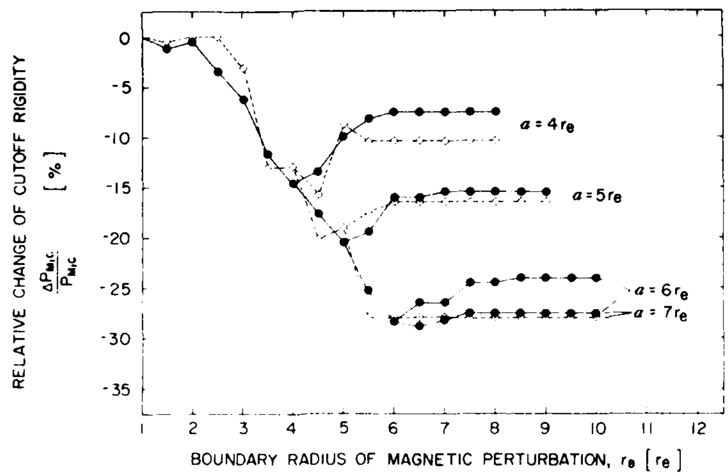

Figure 9. Relative Changes in the Vertical Main Cutoff (◇), and in the Effective Vertical Cutoff Rigidity (●) at Kiel as a Function of the Boundary Radius, r_B, of a Magnetic Disturbance According to Eqs. (4) and (5) With $B''_z(r = a) = -100$ nT and a = 4, 5, 6 and 7r_e Superposed Upon the Main Dipole Field (see text for details). The corresponding undisturbed cutoff rigidities are: P_M = 1.33 GV, and P_C = 1.70 GV

the main cutoff as well as the effective cutoff rigidity show a clearly marked dependence on the relative location of the magnetic perturbation with respect to the station. A maximum change in the main cutoff rigidity of -8.9% results for T = 135°, [illegible], when the station is located at the western boundary of the longitude sector containing the disturbance field. Practically no change occurs in the regions 0 ≤ T ≤ 45° and 270° ≤ T ≤ 360°, that is, when the station is in a longitude sector extending from the eastern boundary of the disturbance field to approximately [illegible]. [illegible] the effective vertical cutoff, maximum changes of the order of [illegible] 150° ≤ T ≤ 165°. In contrast to the results obtained for the main cutoff, [illegible] change in the effective cutoff of [illegible] to -4 [illegible] is found [illegible] station [illegible] of the disturbance field. Similar results have been obtained for [illegible] in Figure 11. At this location, however, significant [illegible] only within the region 60° ≤ T ≤ 110°, that is, [illegible] inside the magnetically perturbed longitude sector. [illegible] cutoff is depressed by approximately [illegible] vertical cutoff [illegible] of the order of [illegible]. [illegible]

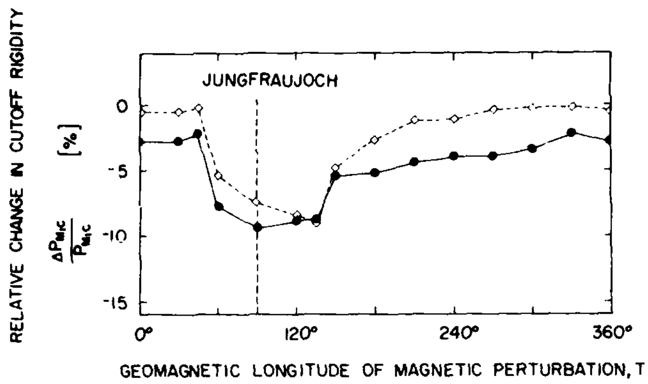

Figure 10. Relative Changes in the Vertical Main Cutoff (◇), and in the Effective Vertical Cutoff Rigidity (●) at Jungfraujoch as a Function of the Longitudinal Position, $T = (\Phi_W + \Phi_E)/2$ of a Magnetic Disturbance According to Eqs. (10) and (5) With $\Phi_E - \Phi_W = 90°$, $B''_z(r \leq a) = -100$ nT and $a = 4r_e$, Superposed Upon the Main Dipole Field (see text for details). The corresponding undisturbed cutoff rigidities are: $P_M = 3.43$ GV, $P_C = 3.22$ GV

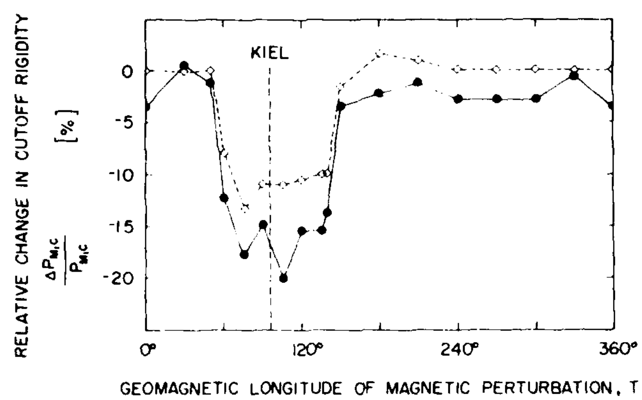

Figure 11. Relative Changes in the Vertical Main Cutoff (◇), and in the Effective Vertical Cutoff Rigidity (●) at Kiel as a Function of the Longitudinal Position, $T = (\Phi_W + \Phi_E)/2$ of a Magnetic Disturbance According to Eqs. (10) and (5) With $\Phi_E - \Phi_W = 90°$, $B''_z(r \leq a) = -100$ nT and $a = 4r_e$, Superposed Upon the Main Dipole Field (see text for details). The corresponding undisturbed cutoff rigidities are: $P_M = 1.83$ GV, $P_C = 1.70$ GV

in the effective vertical cutoff rigidity at Jungfraujoch are shown as a function of the geomagnetic longitude of the eastern boundary, Φ_E, of the longitude sector

containing the disturbance field, with the station being located at the western boundary, that is, with $\Phi_W = \Phi_{JJ}$. The magnetic perturbation is again characterized by $B''_z(r < a) = -100$ nT and $a = 4r_e$. The data show an extremely strong dependence of $\Delta P/P$ on the longitudinal width of the perturbed sector, $W = \Phi_E - \Phi_{JJ}$, in the range $0° \leq W \lesssim 30°$. For $W \approx 60°$ the resulting changes in the cutoff rigidities already amount to ~80% of the final value obtained for the $W > 90°$. It can be concluded therefore, that cutoff changes at midlatitude stations are mainly determined by the magnetic configuration within a longitude sector extending from the longitude of the station to approximately 60° east of it. Figure 13, finally, shows the corresponding results obtained for Kiel. It is again found that both the vertical main cutoff as well as the effective vertical cutoff rigidity are extremely sensitive to magnetic perturbations above and up to ~30° to the east of the station. For magnetic disturbances with longitudinal width $30° \lesssim W \lesssim 60°$ the maximum changes in the cutoff rigidities are of the order of -20%. It is interesting to note that these changes are by a factor of ~1.25 larger than the depressions resulting for $W > 90°$, that is, for magnetic perturbations with a large longitudinal extent.

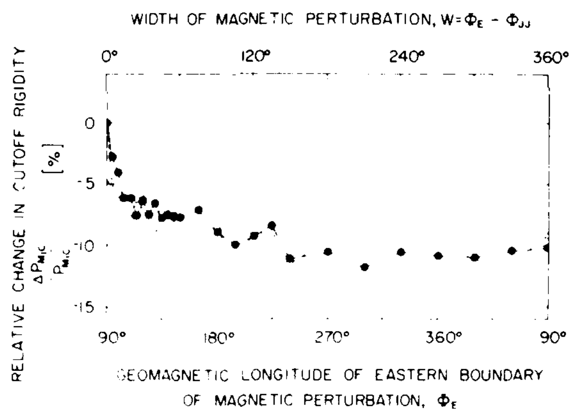

Figure 12. Relative Changes in the Vertical Main Cutoff (◇), and in the Effective Vertical Cutoff Rigidity (●) at Jungfraujoch as a Function of the Geomagnetic Longitude of the Eastern Boundary, Φ_E, of a Magnetic Disturbance According to Eqs. (10) and (5) With $\Phi_W = \Phi_{JJ}$, $B''_z(r < a) = -100$ nT and $a = 4r_e$, Superposed Upon the Main Dipole Field (see text for details). The corresponding undisturbed cutoff rigidities are: $P_M = [illegible].43$ GV $P_C = [illegible].22$ GV

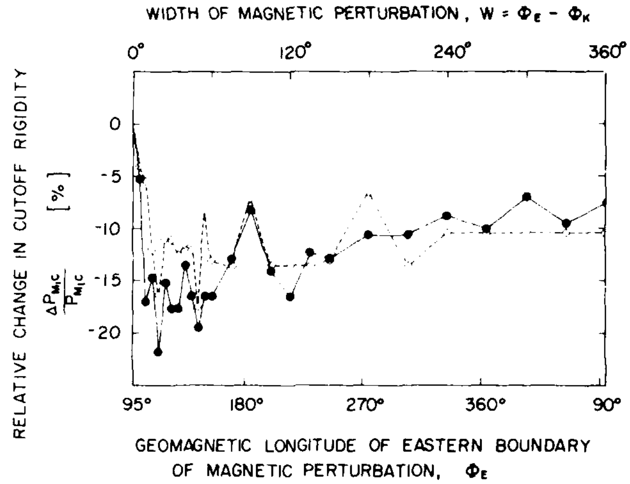

Figure 13. Relative Changes in the Vertical Main Cutoff (◇), and in the Effective Vertical Cutoff Rigidity (●) at Kiel as a Function of the Geomagnetic Longitude of the Eastern Boundary, Φ_E, of a Magnetic Disturbance According to Eqs. (10) and (5) With $\Phi_W = \Phi_K$, $B''_z(r \geq a) = -100$ nT and $a = 4r_e$, Superposed Upon the Main Dipole Field (see text for details). The corresponding undisturbed cutoff rigidities are: $P_M = 1.83$ GV, $P_C = 1.70$ GV

Based on the results of the simple study presented in this section, the following main conclusions could be drawn:

- at low and midlatitude stations ($|\Lambda| \leq 50°$) changes in the cutoff rigidities are mainly determined by variations of the z-component of the magnetic field within a longitude sector extending from the longitude of the station to approximately 60° east of it and within geocentric distances $r < 4r_e \cdot \cos^2\Lambda$; and
- at locations with geomagnetic latitudes $50° \leq |\Lambda| \leq 65°$ changes in cutoff rigidities are mostly due to variations of the z-component of the magnetic field within a longitude sector extending from the longitude of that particular location to approximately 90° east of it and within geocentric distances $r < 10r_e \cdot \cos^2\Lambda$.

5. THE EFFECT OF A PARTIAL RING CURRENT AND OF FIELD-ALIGNED CURRENTS ON COSMIC RAY CUTOFF RIGIDITIES AND ON ASYMPTOTIC DIRECTIONS

In a second study, the effect of a partial ring current and the effect of field-aligned currents on the cutoff rigidities at Kiel, Jungfraujoch and Rome (see Table 1 for corresponding station data), and on the asymptotic directions of cosmic ray particles arriving at these locations was investigated. This analysis was based on the model current systems shown in Figures 14 and 15, corresponding to the Boström No. 1 and 2 Models (Boström[20]). The magnetic fields of the current systems have been calculated according to the method proposed by Kisabeth and Rostoker.[21] Contributions by currents induced in the ground were taken into account by approximating the earth as an infinitely conducting sphere covered by a perfect insulator of depth D (D = 250 km). The International Geomagnetic Reference Field appropriate for Epoch 1965.0, in geomagnetic coordinates (Mead[13]), was used to describe the quiescent field; the perturbed model was represented by the superposition of the magnetic fields generated by the respective model current systems and the quiescent field.

Figure 14. Side and Top View of Model Current System No. 1 (partial ring current) and Definition of its Descriptive Parameters

20. Boström, R. (1964) A model of the auroral electrojet, J. Geophys. Res. 69:4983.

21. Kisabeth, J.L., and Rostoker, G. (1977) Modelling of three-dimensional current systems associated with magnetospheric substorms, [illegible]

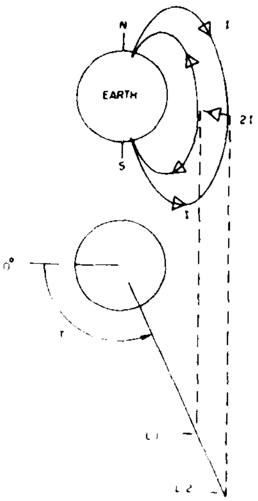

Figure 15. Side and Top View of Model Current System No. 2 and Definition of its Descriptive Parameters

We first discuss the cutoff variations caused by a Model No. 1 current system with $W = 90°$, $L = 4\, r_e$, $I = 2 \cdot 10^6$ A, and an altitude of the ionospheric currents $H = 100$ km. According to Fukushima and Kamide[7] such a current system is representative of the magnetic disturbances observed during magnetic storms in the evening sector. It produces a maximum decrease of the equatorial magnetic field at $r = 1\, r_e$ of 160 nT, with the magnetic flux density $B_\Lambda(r, \Lambda = 0°, \Phi)$ in the equatorial plane depending on geomagnetic longitude and radial distance as shown in Figure 16. In Figure 17a the relative variation of the vertical main cutoff, P_M, and of the effective cutoff, P_C, as a function of the longitude of the center meridian of the current system, T, is shown for Kiel. The maximum effect with the main vertical cutoff lowered by 24.5% and the effective vertical cutoff decreased by 26.5% is found for $T = 120°$, that is, when the station is located near the western boundary of the longitude region with maximum perturbation of the equatorial magnetic field. In Figure 17b corresponding results are shown for the mid-latitude station Jungfraujoch. It is obvious that especially the variation of the effective cutoff shows a much more pronounced dependence on T at Kiel in comparison with Jungfraujoch. This result is in agreement with the fact pointed out by Dorman[5] that the typical cosmic ray increases observed during geomagnetically active periods depend more clearly on longitude for stations with small geomagnetic threshold than for low-latitude stations. The latitudinal structure of the cutoff changes caused by a Model No. 1 current and its dependence on the radius of the partial ring current are illustrated in Table 2. Here the relative variation of the effective vertical cutoff rigidity normalized to the maximum change in the equatorial surface magnetic field and averaged over the interval $90° \le T \le 120°$, is listed, for the stations Kiel, Jungfraujoch and Rome. It is evident that the cutoff variations at Kiel depend

significantly on the radius L whereas at Jungfraujoch and Rome they do not. The resulting latitude effect is a characteristic property of the particular geometrical structure of the current system.

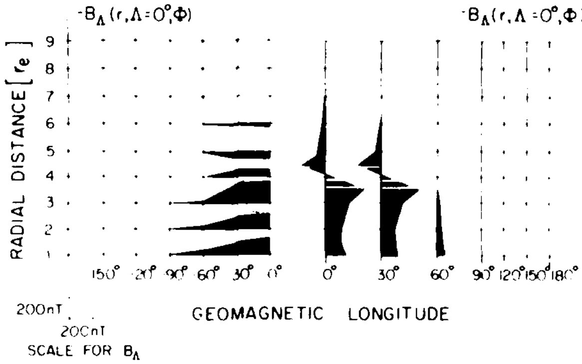

Figure 16. Magnetic Flux Density $B_\Lambda(r, \Lambda = 0°, \Phi)$ in the Equatorial Plane of a Current System According to Model No. 1 (partial ring current) with $T = 0°$, $W = 90°$, $L = 4r_e$ and $I = 2 \cdot 10^6 A$, as a Function of Geomagnetic Longitude and Radial Distance

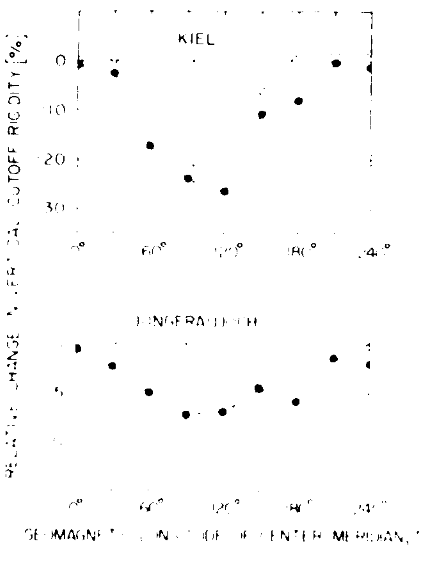

Figure 17. Longitudinal Effect of Model Current System No. 1 With $W = 90°$, $L = 4r_e$ and $I = 2 \cdot 10^6 A$, on the Vertical Main Cutoff (◇) and on the Effective Vertical Cutoff Rigidity (●) at Kiel and Jungfraujoch

Table 2. Effect of Model Current System No. 1 (partial ring current) With W = 90° on the Effective Vertical Cutoff Rigidity at Kiel, Jungfraujoch and Rome, Averaged for 90° ≤ T ≤ 120° and Normalized to the Maximum Change in the Equatorial Surface Magnetic Field

Station	Effective Vertical Cutoff Rigidity (IGRF, Epoch 1965.0) [GV]	Normalized Relative Change in Effective Vertical Cutoff Rigidity [% / 100 nT]		
		$L = 3r_e$	$L = 4r_e$	$L = 5r_e$
Kiel	2.26	8.5 ± 0.5	15.8 ± 0.5	19.8 ± 0.6
Jungfraujoch	4.47	4.6 ± 0.5	5.3 ± 0.5	4.3 ± 0.6
Rome	6.16	3.5 ± 0.2	3.5 ± 0.2	3.4 ± 0.2

The effect of a partial ring current on asymptotic directions is illustrated in Figures 18 and 19. Both figures refer to cosmic ray particles arriving from the vertical direction at Jungfraujoch, and to a current system with the parameters $\Gamma = 90°$, $W = 90°$, $L = 4r_e$ and $I = 2 \cdot 10^6$ A. In Figure 18, the asymptotic directions obtained for specific rigidities in the perturbed geomagnetic field model are compared to corresponding results obtained by using the IGRF, Epoch 1965.0. In Figure 19 the absolute changes of the asymptotic directions in longitude and latitude are plotted as a function of the rigidity of the particles. It can be seen that for rigidities $P > 5.5$ GV the effect is mainly restricted to a westward shift in longitude with amplitudes $|\Delta\psi| < 25°$. As the rigidity decreases below $P \approx 5.5$ GV, the magnitude of the effect increases strongly, reaching maximum changes in both asymptotic longitude and latitude for rigidities just above the value of the quiescent main cutoff. It is interesting to note, however, that the asymptotic direction corresponding to the respective main cutoff rigidity remains practically unchanged, regardless of the actual value of the main cutoff rigidity.

Due to the fact that the effects of magnetospheric current systems on cutoff rigidities and on asymptotic directions are closely correlated, all the results describing the dependence of the cutoff changes on the parameters of the current system apply analogously to variations of the asymptotic directions.

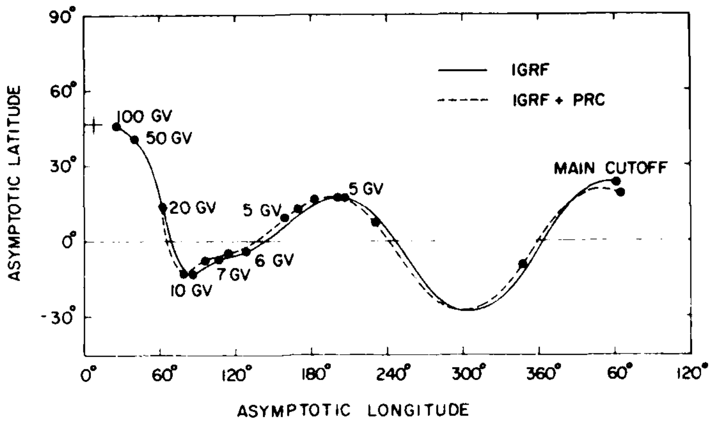

Figure 18. Effect of a Current System According to Model No. 1 (partial ring current, PRC) With T = 90°, W = 90°, L = $4r_e$ and I = $2 \cdot 10^6$A, on the Asymptotic Directions for Cosmic Ray Particles of Vertical Incidence at Jungfraujoch (+)

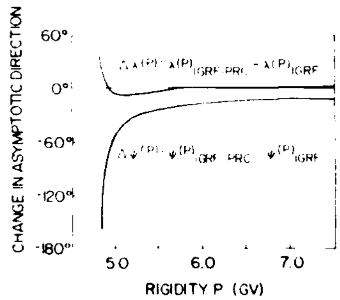

Figure 19. Changes in Asymptotic Latitude, λ, and Longitude, ψ, of Cosmic Ray Particles, Incident From the Vertical Direction at Jungfraujoch, Due to a Current System According to Model No. 1 (partial ring current, PRC) With T = 90°, W = 90°, L = $4r_e$, and I = $2 \cdot 10^6$A

The effects of field-aligned currents on cosmic radiation are in general less pronounced compared to the effects caused by a partial ring current. The longitudinal effect of a model current system according to Figure 15 is illustrated in Figure 20, for the parameters L1 = $4r_e$, L2 = $5.5r_e$, I = $2 \cdot 10^6$A and H = 100 km. In this plot the relative variation of the main cutoff and of the effective vertical cutoff at Kiel are shown as a function of the longitudinal position of the current system. For the specified directions of the current vectors, the cutoff rigidities are increased when the station is located more than ~5° west of the current system. For the main cutoff a maximum increase of 3.6% occurs for T = 117° whereas the effective cutoff rigidity shows a maximum increase of 4.8% at T = 105°. The cutoff rigidities are decreased when the station is situated east of the current system. The maximum depression of the main cutoff is found for T = 90° with an amplitude

of 8.4%. For the effective cutoff a maximum decrease of 5.7% results at T = 82°. A similar, but less pronounced longitudinal structure is found at midlatitudes indicating that the amplitude of the effect depends strongly on latitude. The latitude dependence of the cutoff changes caused by a Model No. 2 current system is illustrated in Figure 21. Here the relative variation of the effective vertical cutoff rigidity for Kiel, Jungfraujoch and Rome averaged over the interval 80° ≤ T ≤ 90° and normalized to the current intensity is plotted as a function of the difference $\Delta\Lambda$ between the geomagnetic latitude corresponding to the foot point of the inflowing field aligned current [Λ_{L1} = arc cos $(r_e/L1)^{0.5}$] and the geomagnetic latitude of the stations, Λ. The different data points have been obtained for L1 = 3.0, 4.0, 5.0 r_e and L2 = 4.5, 5.5, 6.5 r_e respectively. As can be seen the resulting correlation can be approximated by an exponential of the form [exp($-\Delta\Lambda$/5.14°)].

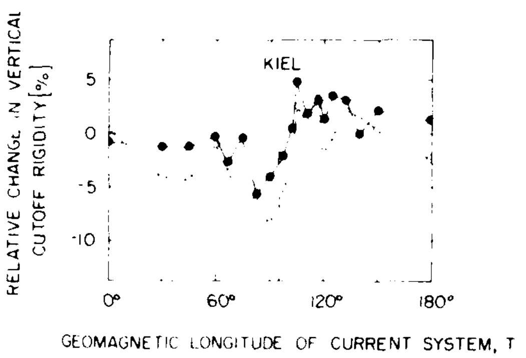

Figure 20. Longitudinal Effect of Model Current System No. 2 With L1 = $4r_e$, L2 = $5.5r_e$ and I = $2 \cdot 10^6$A on the Vertical Main Cutoff (◇) and on the Effective Vertical Cutoff Rigidity (●) at Kiel

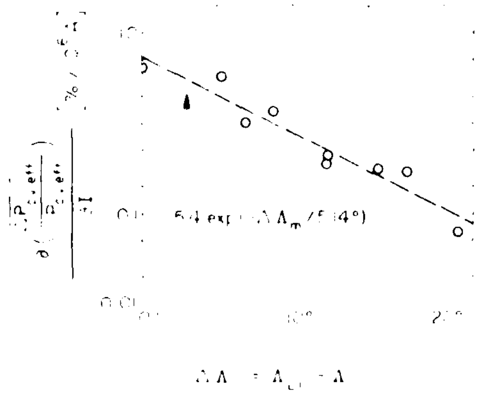

Figure 21. Average Effect of Model Current System No. 2 on the Effective Vertical Cutoff Rigidity at Geomagnetic Longitude Φ = 95° for 80° ≤ T ≤ 90°

Due to the fact that in this analysis the IGRF has been used to model the quiescent geomagnetic field, the quantitative results obtained can actually be related to real experimental measurements and observations. In particular, a comparison of theoretical and experimental data will allow us to verify and adjust the geometry and intensity of the main current systems used to model the disturbed magnetosphere.

6. SIGNIFICANCE OF THE RESULTS

The results of the work presented in this report are of significance for both magnetospheric studies and cosmic ray research.

For the study of the perturbed magnetosphere it is the technical aspect which is important. The procedure which brings together the concepts for currents in the magnetosphere into a model which can be used on a computer is now firmly established. Great flexibility is provided since any type of current system can be included. In addition it could clearly be demonstrated that this procedure can successfully be used to simulate the propagation of cosmic ray particles through the perturbed magnetosphere. Models of magnetospheric current systems can, therefore, not only be related to measurements of the magnetic field but also to actual experimental cosmic ray data. Our results show that changes in cosmic ray cutoff rigidities reflect somehow the integral of the magnetic disturbance field along the particle trajectories. Consequently, cosmic ray data can be useful as an additional tool for the determination and the verification of the specifications used in the models describing the magnetospheric currents developing during geomagnetic storms. Corresponding studies are now in progress and they are expected to help in clarifying the controversy about Birkeland currents as the cause of the low-latitude asymmetric disturbance field (Crooker and Siscoe;[22] Rostoker et al[23]).

This new field of application for cosmic ray measurements is, of course, of great significance for cosmic ray research also. In this domain, however, of equal importance is the substantial improvement in the fundamental understanding of cosmic ray observations during geomagnetically active periods as a consequence of the new quantitative knowledge of the correlation between specific local perturbations

22. Crooker, N.U., and Siscoe, G.L. (1981) Birkeland currents as the cause of the low-latitude asymmetric disturbance field, J. Geophys. Res. 86:11201.
23. Rostoker, G., Mareschal, M., and Samson, J.C. (1982) Response of [illegible] Net Downward [illegible] Changes in the [illegible] The University of Alberta, [illegible], Alberta, Canada.

in the geomagnetic field and their effects on cutoff rigidities and asymptotic directions. In particular, our calculations show that the method which was up to now generally used by cosmic ray physicists to calculate changes in cutoff rigidities from the average worldwide depression of the equatorial surface magnetic field during geomagnetic storms, that is, from the parameter D_{st} (Obayashi;[24] Flückiger et al[25]), can lead to substantial errors of the order of up to 100%. The proper analysis has to take into account the asymmetric longitudinal structure of the magnetic perturbation. A method which makes allowance for this effect will be proposed in another report.

Of further significance is also the fact that the present study clearly indicates that in order to be able to describe the propagation of cosmic ray particles of rigidities $P < 2$ GV through the domain of the earth's magnetic field in full consistence with the observations, even the model of the quiescent geomagnetic field should include the contributions due to external sources. The technique presented in this report allows for this effect and can, therefore, be essentially useful in the study of the origin of particles incident at the earth at high latitudes, especially in the vicinity of open field lines. This problem is still not solved satisfactorily although it is of considerable interest for many applications (Debrunner and Lockwood[26]). Finally, from an inspection of all the results obtained in this study relating the changes in cutoff rigidities and in asymptotic directions with specific magnetic perturbations, and from the comparison of the magnitude of these disturbances as a function of geocentric distance, geomagnetic latitude and longitude with the actual magnitude of the external contributions to the geomagnetic field it can be concluded that from the point of view of cosmic ray research for the representation of the main geomagnetic field there is probably no need to include spherical harmonics with orders much higher than nine.

In summarizing, the new insight obtained in this study into the effect of perturbations of the geomagnetic field on the propagation of cosmic ray particles near the earth will certainly enable an improved analysis of cosmic ray data obtained during magnetically active periods and hopefully lead to an increased use of cosmic ray measurements as an additional tool in the study of the disturbed magnetosphere.

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